

Magnetic-Field Generation and Particle Acceleration in Relativistic Shear Layers

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Abstract. Both observational evidence and theoretical considerations suggest that the relativistic jets of AGN and GRBs are likely to be cylindrically stratified with a fast, inner spine and a slower, outer sheath. The resulting relativistic shear layer is expected to be a site of self-generation of magnetic fields due to the Weibel instability, and of relativistic particle acceleration. We here present first results of particle-in-cell (PIC) simulations of relativistic shear layers in both electron-proton and electron-positron jets. We demonstrate that magnetic fields close to equipartition can be self-generated in initially unmagnetized flows, and strong electric fields and MHD turbulence in the shear layer lead to the acceleration of highly anisotropic particle distributions. The resulting highly beamed synchrotron and Compton emission, in addition to beaming due to the bulk motion of the plasma, may offer a solution to the Lorentz factor crisis for AGN jets.

Keywords: Active and peculiar galaxies and related systems; gamma-ray sources; jets and bursts

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INTRODUCTION

There are several lines of evidence which suggest that the jets in blazars (and likely also GRBs) exhibit at least a two-component structure: A mildly relativistic, outer jet (sheath) carries most of the kinetic energy of the jet, while a fast, highly relativistic inner jet (spine) of low co-moving particle density carries most of the angular momentum. Direct observational evidence for radially structured jets comes from limb-brightening of blazar and radio galaxy jets revealed in VLBI observations [e.g., 2]. Prompted by such evidence, Ghisellini et al. [1] proposed the radiative interaction between a fast, inner spine and a slower sheath in a blazar jet as a way to overcome problems with extreme bulk Lorentz factors required by spectral fits to several TeV BL Lac objects, which are in contrast to the much lower bulk Lorentz factors inferred from high-resolution (VLBI) radio observations. This problem is sometimes referred to as the *Lorentz factor crisis* [5].

HD/MHD simulations of spine-sheath jets [e.g. 9, 10, 11], indicate that the sheath, in combination with a poloidal magnetic field, aids in stabilizing the jet. Although Rayleigh-Taylor-type instabilities may develop at the spine-sheath interface and lead to turbulent mixing of the two phases, they may not disrupt the jet out to large distances from the central engine [9, 10]. The turbulence developing at the spine-sheath interface of relativistic jets offers a promising avenue for relativistic particle acceleration in radio-loud AGN and GRBs.

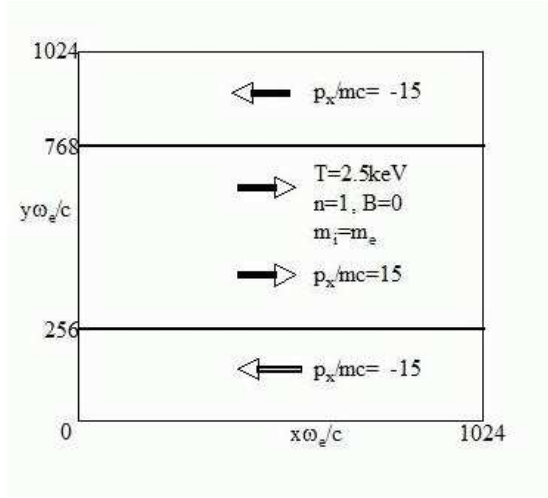


FIGURE 1. Sketch of the model setup for out PIC simulations of shear layers in radially stratified relativistic jets

A major problem with our current understanding of the physics of blazar (and GRB) jets is that the physical phenomena of jet formation, collimation, particle acceleration on the one hand, and radiation on the other hand, are treated as completely separate problems. There is an extensive body of literature which treats the physics of jet launching, collimation, and stability, quite often with hydrodynamical, MHD, or even General Relativistic MHD simulations [e.g., 6, 9, 11, 7, 14, 8, 10]. Due to the nature of HD/MHD, the details of individual particle acceleration are not considered in these simulations. This makes reliable predictions of the expected radiative output from the various jet launching/collimation scenarios impossible.

The dynamics of individual particles are successfully simulated in Particle-in-Cell (PIC) simulations [e.g., 3, 12, 13, 4]. Such simulations indicate that particle acceleration at relativistic shocks, shear layers, and/or current sheets often leads to the development of a Maxwellian and a high-energy tail.

In this paper, we present first result from an on-going project using PIC simulations to study the self-consistent magnetic-field generation and particle acceleration in relativistic shear layers, as believed to be present in radially stratified, relativistic jets of AGN and GRBs. The results will be used in future work to make detailed prediction about the spectral and polarization properties of the synchrotron and Compton emission produced in this scenario.

MODEL SETUP

The initial conditions for our 2D PIC simulations of relativistic shear layers are illustrated in Figure 1. The simulations are performed in a reference frame in which the inner spine and the outer sheath are counter-streaming with equal, but opposite velocities. Both plasmas are assumed to be initially cool and unmagnetized. Ion-to-electron mass ratios of $m_i/m_e = 1$ (electron-positron plasma) and $m_i/m_e = 1836$ (electron-proton

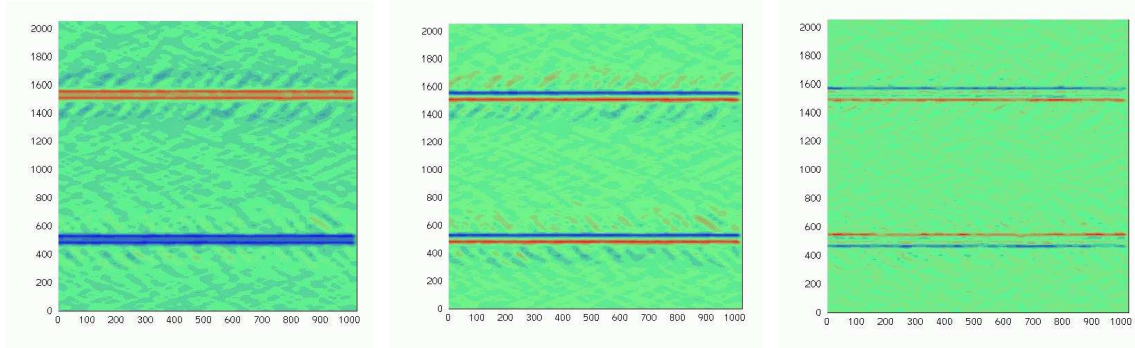


FIGURE 2. Left: Magnetic field B_z (in the plane of the shear layer); center: Electric field E_y (direction across the shear layer); right: Electric current J_x (along the direction of the flow) for an e-p plasma.

plasma) have been considered. The jet axis defines the x axis, the y axis is oriented in the radial direction (across the shear layer), while the z axis extends along the shear layer, perpendicular to the direction of the flow. The cell size for the simulations is set equal to the plasma skin depth, $\Delta x = c/\omega_e$. Doubly-periodic boundary conditions are imposed in the x and y directions.

MAGNETIC- AND ELECTRIC-FIELD GENERATION

Figure 2 illustrates the self-generated magnetic field B_z (left), electric field E_y (center), and electric current J_x (right) in the case of a run for an electron-proton plasma with $p_x/(mc) = \pm 15$. These are the most significant (large-scale) components of the magnetic and electric fields.

Our simulations show that the shear boundary layer becomes unstable to both longitudinal and transverse modes with initial wavelengths $\sim$ several hundred skin depths. They lead to organized currents in the direction of the shear flow, generating large-scale, ordered magnetic fields in the plane of the shear layer, which can reach values near equipartition with the plasma. At the same time, electric fields are generated in the y direction, which significantly accelerate electrons and ions in the direction perpendicular to the shear layer.

PARTICLE ACCELERATION

Figure 3 (left) illustrates the acceleration of electrons in the x direction, i.e., along the direction of the flow. This snap-shot was taken at an early time in the simulation, before ion instabilities are fully developed. The angle-averaged particle distribution $f(\gamma)$, shown in Figure 3 (right), resembles a highly relativistic Maxwellian. However, we expect that, once ion instabilities are fully developed, a non-thermal tail in the electron distribution will be formed.

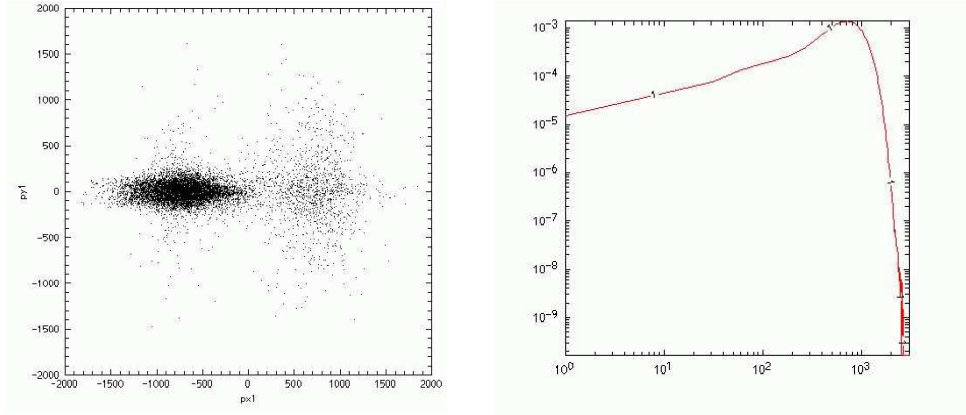


FIGURE 3. Left: Scatter plot of electron momenta ($p_{x,y}/(m_e c)$) within the spine. Right: Angle-averaged particle distribution $f(\gamma)$.

DISCUSSION

Our PIC simulations have shown that relativistic shear layers in radially stratified, relativistic jets can efficiently self-generate ordered magnetic fields near equipartition, and lead to highly anisotropic particle acceleration. The radiative signature of this acceleration will be highly polarized synchrotron and Compton emission. The strongly anisotropic particle distribution will lead to equally strongly beamed synchrotron and Compton emission, adding to the Doppler boosting due to the relativistic bulk motion of the jet. We suggest that this may be a solution to the Lorentz factor crisis of AGN jets.

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